PB88-125521

Estimating Sample Requirements for Field Evaluations of Pesticide Leaching

(U.S.) Environmental Research Lab., Athens, GA

1987

U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RE PB88-125521
EPA/600/J-87/090		

4. TITLE AND SUBTITLE	5. REPORT DATE
ESTIMATING SAMPLE REQUIREMENTS FOR FIELD EVALUATIONS OF PESTICIDE LEACHING (Journal Version)	1987
	6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
Charles N. Smith, Rudolph S. Parrish* and Robert F. Carsel	

9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
Environmental Research Laboratory, U.S. Environmental Protection Agency, Athens, GA 30613 *Computer Sciences Corporation, Environmental Research Laboratory, Athens, GA 30613	ACBE1A
	11. CONTRACT/GRANT NO.

12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
Environmental Research Laboratory - Athens, GA Office of Research and Development U.S. Environmental Protection Agency Athens, GA 30613	14. SPONSORING AGENCY CODE EPA/600/01

15. SUPPLEMENTARY NOTES

In: Environmental Toxicology and Chemistry, 6(5):343-357, May 1987

16. ABSTRACT

A method is presented for estimating the number of samples needed to evaluate pesticide leaching threats to ground water at a desired level of precision. Sample size projections are based on desired precision (exhibited as relative tolerable error), level of confidence (90 or 95 %), and estimates of variability (expressed as the coefficient of variation) for selected pesticide and soil characteristics. Summary tables of descriptive statistics are provided as guides for projecting variability of various soil characteristics, pesticide properties (sorption, degradation), pesticide concentration profiles and inorganic solutes. These data were compiled through a comprehensive search of review articles and of reports of laboratory and field studies. The parameters selected are measurements generally required for conducting field pesticide leaching studies. They also are useful for evaluating ground water contamination by calibrating and conducting sensitivity testing with solute transport models. Results show that sample size estimates (for constant desired precision and confidence level) for characterizing selected soil characteristics generally are smaller than those required for estimating pesticide concentrations. Fewer samples are projected for estimating pesticide concentrations shortly after application, with progressive increases required for later sampling.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

REPRODUCED BY
U.S. DEPARTMENT OF COMMERCE
NATIONAL TECHNICAL
INFORMATION SERVICE
SPRINGFIELD, VA. 22161

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
RELEASE TO PUBLIC	UNCLASSIFIED	17
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22. PRICE PC $12.95/ MF 6.95

EPA Form 2220-1 (9-73)

EPA/600/J-87/090
JOURNAL ARTICLE

Environmental Toxicology and Chemistry, Vol. 6, pp. 343-357, 1987
Printed in the USA. Pergamon Journals Ltd.

0730-7268/87 $3.00 + .00

ESTIMATING SAMPLE REQUIREMENTS FOR FIELD EVALUATIONS OF PESTICIDE LEACHING

CHARLES N. SMITH,* RUDOLPH S. PARRISH† and ROBERT F. CARSEL
Environmental Research Laboratory, U.S. Environmental Protection Agency,
Athens, Georgia 30613, and †Computer Sciences Corporation,
Environmental Research Laboratory, Athens, Georgia 30613

(*Received* 22 *April* 1986; *Accepted* 20 *October* 1986)

Abstract—A method is presented for estimating the number of samples needed to evaluate pesticide leaching threats to ground water at a desired level of precision. Sample size projections are based on desired precision (exhibited as relative tolerable error), level of confidence (90 or 95%) and estimates of variability (expressed as the coefficient of variation) for selected pesticide and soil characteristics.

Summary tables of descriptive statistics are provided as guides for projecting variability of various soil characteristics, pesticide properties (sorption, degradation), pesticide concentration profiles and inorganic solutes. These data were compiled through a comprehensive search of review articles and of reports of laboratory and field studies. The parameters selected are measurements generally required for conducting field pesticide leaching studies. They are also useful for evaluating ground water contamination by calibrating and conducting sensitivity testing with solute transport models. Coefficients of variation for selected soil characteristics were as follows: bulk density, 2 to 17%; organic matter, 42 to 125%; porosity, 4 to 18%; particle size distribution, 3 to 55%; hydrogen ion activity, 2 to 15%; 0.3 bar water content, 18 to 82%; 15 bar water content, 18 to 87%; saturated hydraulic conductivity, 48 to 320%; and infiltration rate, 40 to 97%.

Coefficients of variation for selected pesticide characteristics were as follows: transformation rates, 7 to 202%; sorption coefficients, 34 to 56%; and pesticide concentration profiles, 40 to 450%. Variability of pesticide concentrations increased over time after the initial pesticide application. The coefficients of variation for inorganic solutes ranged from 19 to 127%.

On the basis of these data, sample size estimates (for constant desired precision and confidence level) for characterizing selected soil characteristics generally are smaller than those required for estimating pesticide concentrations. Fewer samples are projected for estimating pesticide concentrations shortly after application, with progressive increases required in later sampling.

Keywords—Variability Coefficient of variation Pesticides Population means

INTRODUCTION

As part of its mandate under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA), the U.S. Environmental Protection Agency (EPA) is required to register and approve proposed pesticides before they are released for widespread application. FIFRA requires that data be submitted to the EPA in support of the registration of a pesticide [1]. These data requirements include results of field studies that evaluate terrestrial fate (including movement to ground water).

Legislative mandates and the regulatory approach for fulfilling them treat pesticides generically and are largely based upon the pesticides' inherent chemical characteristics. One obvious problem with this requirement to regulate pesticides on a generic basis is that the environmental risk is influenced by site-specific factors.

The appearance of pesticide residues in ground water [2] has received considerable attention during the last few years. The U.S. EPA [3] reported that organic solutes (e.g., pesticides and chemical wastes) in ground water have been identified only through discovery of the compounds in water-supply wells. Pesticides in water supplies have been identified (at low parts-per-billion concentrations) mostly in near-field wells in unconfined surficial aquifers [4]. Environmental issues to be considered are that agricultural pesticides are most likely to appear in shallow near-field wells, that long periods will elapse before the extent of a problem is detectable, and that the chemicals may have a substantial adverse impact on selected aquifer systems.

The assessment of ground water contamination

*To whom correspondence may be addressed.

NTIS is authorized to reproduce and sell this report. Permission for further reproduction must be obtained from the copyright owner.

by pesticides used in agriculture invariably includes evaluating the transport of the compounds through the unsaturated soil zone. In many instances, the magnitude of the contamination depends on the pesticide's residence time in that portion of the soil profile. Residence time is determined by the characteristics of the individual pesticide and of the wide variety of soils into which the compound moves. The soils literature contains numerous assessments documenting the variability associated with the textural and hydraulic characteristics of soils [5,6].

The coefficient of variation (C.V.) is often used as a measure of variability. The C.V. is often highest for soil hydraulic properties (e.g., hydraulic conductivity) and lowest for properties such as bulk density and total porosity [7,8].

Assessments of the variability associated with pesticide characteristics are not as extensively reported in the literature. High C.V.'s have been reported for pesticide concentrations [9,10]. Amoozegar-Fard et al. [11] reported that the C.V. for selected pesticides increased over time. Lower variability (e.g., C.V. less than 100%) has been reported for transformation and sorptive characteristics [9,10,12–14]. These spatial variations and their effect on solute movement [15,16] can have important implications for assessments of ground water pesticide contamination.

Rao and Wagenet [12] proposed that efficient sampling strategies must be developed to obtain unbiased estimates of field variability as it influences pesticide fate. The design of field sampling programs can be based on either geostatistical or classical statistical methods. To the authors' knowledge, there have been no comparisons made between the two methods.

The geostatistical method requires estimates of spatial variances and correlations. Unfortunately, these types of data generally are not available for pesticides. The classical statistical approach uses randomness as a basic component. The term randomness implies that any individual sample has an equal chance of being selected from a well-defined population. Although the geostatistical approach may ultimately provide the most rigorous techniques for estimating sample locations and parameter values, the lack of spatial correlation measurements for pesticides makes the classical approach the most practical.

This article describes a statistical method for determining sample-size requirements for given levels of confidence as applied to pesticide leaching studies based on measures of variability. The basic premise is that observed variations in soil and pesticide properties and field soil-profile pesticide concentrations can be used as estimates of variability. Summary tables are provided as guides for projecting the variability of soil characteristics and the degradation and sorption properties of pesticides. Additional data are provided for variability estimates of soil depth profiles for selected pesticides.

SAMPLE SIZE ESTIMATION

Sample size refers to the number of individual, independent measurements needed to estimate a given population parameter with specified accuracy and confidence. Various sampling designs can be employed to fulfill the objectives of the planned study to provide estimates of different measurement parameters of interest. Smith et al. [17] published guidelines for selecting sample sizes in monitoring applications using classical statistical methods based on random sampling. The general formula for the sample size required in random sampling to estimate a given population mean is

$$n \geq (ts/d)^2 \qquad (1)$$

where t is a percentile $(1 - \alpha/2)$ of Student's t distribution for the given sample size with $(n - 2)$ degrees of freedom; s is the estimate of the population standard deviation; and d is the largest acceptable difference between the estimate and true mean value (tolerable error) at the given level of confidence. The estimate of population standard deviation, s, relates to inherent variability and is required before the main sampling procedure can be carried out; t is dependent on the level of risk as well as on the sample size, n; and d is dependent on the accuracy required. These and other factors, such as resource allocation, will determine the total sample size requirement.

The application of Equation 1 requires a prior estimate of variability. If the true standard deviation, σ, were known, then from Equation 1, n could be determined by

$$n \geq (t\sigma/d)^2 \qquad (2)$$

By definition, in terms of population parameters,

$$\text{C.V.} = (\sigma/\mu)*100$$

Thus,

$$\sigma = \text{C.V.}*\mu/100$$

where C.V. is the coefficient of variation and μ is the population mean. Further, the tolerable error may be expressed as

$$d = \mu * A/100$$

where A is the desired accuracy as a percentage of the mean. The equality

$$\frac{\sigma}{d} = \frac{\text{C.V.}}{A}$$

yields, for Equation 2,

$$n \geq t^2(\text{C.V.}/A)^2 \quad (3)$$

Sample sizes were determined using Equation 3 for selected C.V.'s, relative tolerable errors and confidence levels. These results are displayed in Figures 1 and 2. Obviously, larger sample sizes are indicated as the C.V. increases and the relative tolerable error decreases. For the 0.90 and 0.95 levels of confidence, sample size estimates gener-

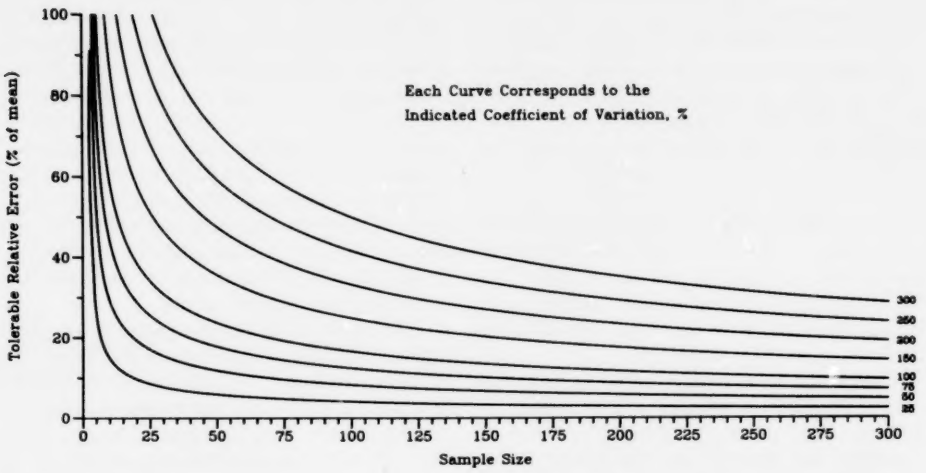

Fig. 1. Projected sample size chart for estimating means from random samples (90% level of confidence).

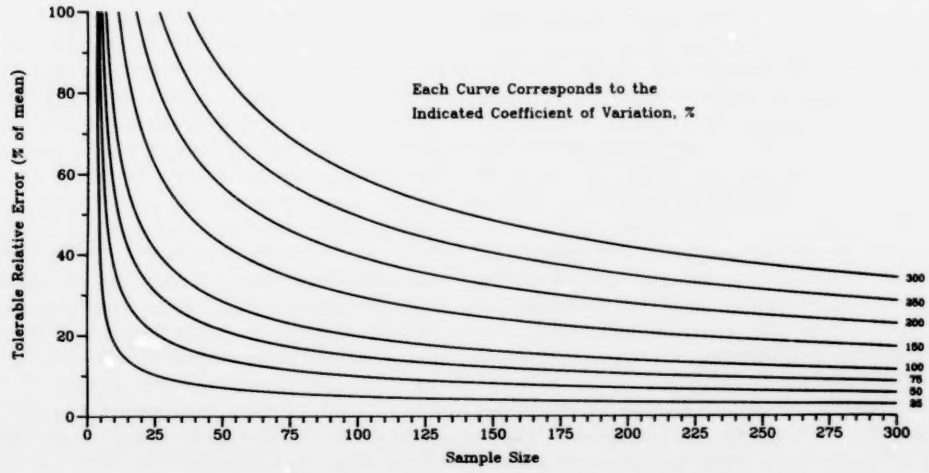

Fig. 2. Projected sample size chart for estimating means from random samples (95% level of confidence).

ally do not differ widely until the C.V. exceeds 100%. For example, at a C.V. of 300%, a tolerable error of 50% and a 90% level of confidence, a sample size of approximately 100 is projected, whereas 150 is projected at the 95% level of confidence. Sample size projections between the two levels of confidence may be critical for soil sampling programs that require intensive labor, such as hand augering techniques.

ESTIMATES OF VARIABILITY

The movement of solutes (e.g., pesticides) into ground water is greatly influenced by chemical and soil characteristics. The interaction of these characteristics with precipitation ultimately determines the timing, magnitude and duration of ground water pesticide contamination. Generally, these characteristics and estimates of variability are not available for site-specific analysis. Mathematical models are frequently used to perform such analyses. The models are used in combination with either sensitivity testing or Monte Carlo simulation to determine the effect of spatial variability relating to the uncertainty of pesticide leaching. The results of the uncertainty estimate can be used to identify areas in which additional laboratory or field investigation is required.

For our study, a comprehensive literature review was conducted of review articles and laboratory and field reports to provide estimates of variability for chemical and soil characteristics. The parameters selected are those generally required for conducting field and/or model evaluations of pesticide movement.

Nielson et al. [6] defined soil characteristics as either capacity (e.g., bulk density, organic matter content, sand or clay content) or intensity (e.g., hydraulic conductivity) factors. These characteristics influence pesticide concentrations both temporally and spatially. The variability estimates for these soil characteristics are given in Table 1. The observed range of C.V.'s for capacity and intensity soil characteristics from Table 1 are as follows: bulk density, 2 to 17%; organic matter, 42 to 125%; porosity, 4 to 18%; particle size distribution, 3 to 55%; 0.3 bar water content, 18 to 82%; 15 bar water content, 18 to 87%; hydrogen ion activity, 2 to 15%; saturated hydraulic conductivity, 48 to 320%; and infiltration rate, 40 to 97%.

The C.V. was smallest for capacity factors such as bulk density and porosity and highest for intensity factors such as saturated hydraulic conductivity. These observations generally agree with those reported elsewhere [7,8]. Most notable are the higher C.V.'s for bulk density reported for Soil Conservation Service hydrological soil groups (A, B, C, D) for the continental United States [18] as compared with those reported for a 3.9-ha field site in the Dougherty Plain area of Georgia. These results indicate less variability within a field than is found between fields.

Pesticide characteristics in soils are usually categorized as transport and transformation properties and as residue (concentration) levels. Pesticides are considered interacting solutes in that their concentration in soil is dependent on chemical-specific factors such as sorption and transformation rates. Soil-water tracers, such as bromide, are generally considered noninteracting and the soil concentrations of these tracers may reflect the inherent (true) field variability. Comparisons of reported variability for inorganic solutes, such as bromide tracer, with pesticide concentrations may provide insight into the effects of chemical-specific factors. Reported variability estimates for inorganic solutes are listed in Table 2. The C.V. ranged from 19 to 127% and did not appear to be influenced by sampling depth.

The results for pesticide transport and transformation characteristics are given in Table 3. The C.V. ranged from 7 to 202% for transformation and was generally less than 100% (excluding organochlorines). For the transport process (sorption), the C.V. ranged from 34 to 56%.

The pesticide concentration results were compiled from two separate field studies [unpublished data from the Dougherty Plain field project; 19] and are displayed in Figures 3 through 5. The overall range for mean C.V. was 40 to 450%. In most cases, the C.V. increased over time after pesticide application. (Similar results were obtained for cyanazine, paraquat, diphenamid, and 2,4-D.) These results compare well with those of Amoozegar-Fard et al. [11] and indicate that sample size requirements may not be static for pesticide soil concentrations. For example, characterizing the leading edge of the concentration profile as opposed to the midpoint of the profile would require more samples (for the same precison). The higher C.V. associated with time after application and sampling depth (as compared with the results for bromide and chloride) indicate that chemical characteristics may contribute to the increased variability. Small concentrations at lower depths and longer times after application often produce observed values of zero and hence contribute to increased C.V.'s.

Table 1. Mean, standard deviation (SD) and coefficient of variation (C.V.) of soil parameters

Parameter	Soil texture	Field area (ha)	Hydro group	Measurement method	Sampling depths (m)	N	Units	Mean	SD	C.V.	Reference
Bulk density	Sandy loam	3.9	—	Undisturbed core	0.00–0.15	19	mg/m³	1.62	0.06	4	—[a]
	Sandy loam	3.9	—	Undisturbed core	0.25–0.43	23		1.60	0.08	5	—[a]
	Sandy loam	3.9	—	Undisturbed core	0.48–0.60	19		1.59	0.06	4	—[a]
	Sandy loam	3.9	—	Undisturbed core	0.60–1.07	23		1.59	0.04	2	—[a]
	Sandy loam	15	—	—	0.00–1.50	64		1.30	0.09	7	[5]
	Sandy loam	1.3	—	Undisturbed core	0.30–1.50	192		1.47	0.13	9	[5]
	Sand	0.34	—	Undisturbed core	0.00–0.15	5		1.65	0.05	3	[5]
	Sand	91.6	—	Undisturbed core	0.00–0.15	5		1.59	0.10	6	[5]
	Silt loam	0.5	—	Undisturbed core	0.15–1.50	72		1.47	0.09	6	[5]
	Silty clay	0.5	—	Undisturbed core	0.15–1.50	144		1.26	0.08	6	[5]
	Clay loam	150	—	Undisturbed core	0.00–1.80	120		1.20	0.09	7	[5]
	—[b]	40	—	Undisturbed core	0.50–0.60	36		1.20	0.18	15	[5]
	—[b]	Rep. U.S.[c]	A	—	0.00–0.30	40		1.45	0.24	16	[18]
	—[b]	Rep. U.S.[c]	A	—	0.30–0.60	44		1.50	0.23	16	[18]
	—[b]	Rep. U.S.[c]	A	—	0.60–0.90	38		1.57	0.16	11	[18]
	—[b]	Rep. U.S.[c]	A	—	0.90–1.20	34		1.58	0.13	8	[18]
	—[b]	Rep. U.S.[c]	B	—	0.00–0.30	459		1.44	0.19	14	[18]
	—[b]	Rep. U.S.[c]	B	—	0.30–0.60	457		1.51	0.19	12	[18]
	—[b]	Rep. U.S.[c]	B	—	0.60–0.90	438		1.56	0.19	12	[18]
	—[b]	Rep. U.S.[c]	B	—	0.90–1.20	384		1.60	0.21	13	[18]
	—[b]	Rep. U.S.[c]	C	—	0.00–0.30	398		1.46	0.22	15	[18]
	—[b]	Rep. U.S.[c]	C	—	0.30–0.60	395		1.58	0.23	15	[18]
	—[b]	Rep. U.S.[c]	C	—	0.60–0.90	371		1.64	0.23	14	[18]
	—[b]	Rep. U.S.[c]	C	—	0.90–1.20	326		1.67	0.23	14	[18]
	—[b]	Rep. U.S.[c]	D	—	0.00–0.30	259		1.52	0.24	16	[18]
	—[b]	Rep. U.S.[c]	D	—	0.30–0.60	244		1.63	0.26	16	[18]
	—[b]	Rep. U.S.[c]	D	—	0.60–0.90	214		1.67	0.27	16	[18]
	—[b]	Rep. U.S.[c]	D	—	0.90–1.20	180		1.65	0.28	17	[18]
	—[b]	Rep. U.S.[c]	—	—	2.44–2.44	111		1.67	0.09	17	[18]
Organic matter	Sandy loam	3.9	—	Walkley-Black	0.00–0.15	25	wt-%	0.94	0.40	42	—[a]
	Sandy loam	3.9	—	Walkley-Black	0.25–0.43	25		0.31	0.14	46	—[a]
	Sandy loam	3.9	—	Walkley-Black	0.48–0.60	25		0.25	0.10	42	—[a]
	Sandy loam	3.9	—	Walkley-Black	0.60–1.07	25		0.15	0.12	81	—[a]
	—[b]	Rep. U.S.[c]	A	—	0.00–0.30	162		0.86	0.79	92	[18]
	—[b]	Rep. U.S.[c]	A	—	0.30–0.60	162		0.29	0.34	114	[18]
	—[b]	Rep. U.S.[c]	A	—	0.60–0.90	151		0.15	0.14	94	[18]
	—[b]	Rep. U.S.[c]	A	—	0.90–1.20	134		0.11	0.11	104	[18]

continued

Table 1 continued

Parameter	Soil texture	Field area (ha)	Hydro group	Measurement method	Sampling depths (m)	N	Units	Mean	SD	C.V.	Reference
	—[b]	Rep. U.S.[c]	B	—	0.00–0.30	1,135		1.30	0.87	68	[18]
	—[b]	Rep. U.S.[c]	B	—	0.30–0.60	1,120		0.50	0.40	83	[18]
	—[b]	Rep. U.S.[c]	B	—	0.60–0.90	1,090		0.27	0.23	84	[18]
	—[b]	Rep. U.S.[c]	B	—	0.90–1.20	1,001		0.18	0.16	87	[18]
	—[b]	Rep. U.S.[c]	C	—	0.00–0.30	838		1.45	1.12	77	[18]
	—[b]	Rep. U.S.[c]	C	—	0.30–0.60	822		0.53	0.61	114	[18]
	—[b]	Rep. U.S.[c]	C	—	0.60–0.90	780		0.28	0.27	96	[18]
	—[b]	Rep. U.S.[c]	C	—	0.90–1.20	672		0.20	0.21	104	[18]
	—[b]	Rep. U.S.[c]	D	—	0.00–0.30	638		1.34	0.87	66	[18]
	—[b]	Rep. U.S.[c]	D	—	0.30–0.60	617		0.65	0.52	80	[18]
	—[b]	Rep. U.S.[c]	D	—	0.60–0.90	558		0.41	0.34	84	[18]
	—[b]	Rep. U.S.[c]	D	—	0.90–1.20	493		0.29	0.31	105	[18]
	—[b]	Rep. U.S.[c]	—	—	2.44–2.44	211		0.05	0.06	125	—[f]
Porosity	Clay loam	150	—	Water content[d]	0.00–1.80	120	m^3/m^3	0.45	0.05	11	[5]
	Sand	0.8	—	—	0.00–0.90	120		0.37	0.04	11	[5]
	Clay loam	0.03	—	Water content[d]	0.00–1.20	20		0.53	0.04	7	[5]
	Loamy sand	0.4	—	Water content[d]	0.00–0.14	12		0.42	0.05	10	[5]
	Sandy loam	3.9	—	Calculated[e]	0.00–0.15	7		0.39	0.02	6	—[a]
	Sandy loam	3.9	—	Calculated[e]	0.25–0.43	7		0.41	0.31	8	—[a]
	Sandy loam	3.9	—	Calculated[e]	0.48–0.60	7		0.41	0.02	5	—[a]
	Sandy loam	3.9	—	Calculated[e]	0.94–1.07	7		0.41	0.02	4	—[a]
	—[b]	Rep. U.S.[c]	—	—	2.44–2.44	111		0.37	0.06	18	—[f]
Particle density	Sandy loam	3.9	—	Pycnometer	0.00–0.15	14	mg/m^3	2.66	0.03	1	—[a]
	Sandy loam	3.9	—	Pycnometer	0.25–0.43	14		2.69	0.02	1	—[a]
	Sandy loam	3.9	—	Pycnometer	0.48–0.60	13		2.70	0.02	1	—[a]
	Sandy loam	3.9	—	Pycnometer	0.94–1.07	14		2.71	0.03	1	—[a]
Particle size distribution	Sandy loam	3.9	—	Hydrometer	0.00–0.15	7	% sand	82.70	4.68	6	—[a]
	Sandy loam	3.9	—	Hydrometer	0.00–0.15	7	% silt	12.60	3.56	28	—[a]
	Sandy loam	3.9	—	Hydrometer	0.00–0.15	7	% clay	4.60	1.60	35	—[a]
	Sandy loam	3.9	—	Hydrometer	0.25–0.43	7	% sand	77.70	6.30	8	—[a]
	Sandy loam	3.9	—	Hydrometer	0.25–0.43	7	% silt	10.70	1.24	12	—[a]
	Sandy loam	3.9	—	Hydrometer	0.25–0.43	7	% clay	11.60	6.16	53	—[a]
	Sandy loam	3.9	—	Hydrometer	0.48–0.60	7	% sand	70.00	4.41	6	—[a]
	Sandy loam	3.9	—	Hydrometer	0.48–0.60	7	% silt	10.30	1.34	13	—[a]
	Sandy loam	3.9	—	Hydrometer	0.48–0.60	7	% clay	19.70	5.02	26	—[a]
	Sandy loam	3.9	—	Hydrometer	0.94–1.07	7	% sand	70.20	5.65	8	—[a]
	Sandy loam	3.9	—	Hydrometer	0.94–1.07	7	% silt	7.60	2.89	38	—[a]
	Sandy loam	3.9	—	Hydrometer	0.94–1.07	7	% clay	22.20	6.50	29	—[a]

	Sandy loam	15	—	—	0.00–1.50	64	% sand	59.00	21.50	37	[5]	
	Sandy loam	15	—	—	0.00–1.50	64	% clay	12.00	6.40	53	[5]	
	Loamy sand	91.4	—	—	0.00–1.50	5	% sand	83.00	2.60	3	[5]	
	Loamy sand	91.4	—	—	0.00–1.50	5	% clay	9.00	3.00	34	[5]	
	Sandy clay loam	0.28	—	—	0.20–0.40	35	% sand	65.00	5.10	8	[5]	
	Sandy clay loam	0.28	—	—	0.20–0.40	35	% clay	28.00	4.90	18	[5]	
	Clay	150	—	Hydrometer	0.00–180.00	480	% sand	24.00	13.50	55	[5]	
	Clay	150	—	Hydrometer	0.00–180.00	480	% clay	45.00	10.50	22	[5]	
Water content at 0.3 bar	Sandy loam	3.9	—	Tempe cells	0.00–0.15	7	g/g	0.07	0.02	23	—[a]	
	Sandy loam	3.9	—	Tempe cells	0.25–0.43	7		0.08	0.03	40	—[a]	
	Sandy loam	3.9	—	Tempe cells	0.48–0.60	7		0.11	0.03	29	—[a]	
	Sandy loam	3.9	—	Tempe cells	0.94–1.07	7		0.13	0.02	18	—[a]	
	—[b]	Rep. U.S.[c]	A	—	0.00–0.30	52	vol-%	11.80	9.20	78	[18]	
	—[b]	Rep. U.S.[c]	A	—	0.30–0.60	50		9.60	7.90	82	[18]	
	—[b]	Rep. U.S.[c]	A	—	0.60–0.90	42		7.30	5.80	79	[18]	
	—[b]	Rep. U.S.[c]	A	—	0.90–1.20	39		7.10	5.00	70	[18]	
	—[b]	Rep. U.S.[c]	B	—	0.00–0.30	459		19.50	8.30	42	[18]	
	—[b]	Rep. U.S.[c]	B	—	0.30–0.60	454		19.00	7.40	39	[18]	
	—[b]	Rep. U.S.[c]	B	—	0.60–0.90	435		18.20	7.10	39	[18]	
	—[b]	Rep. U.S.[c]	B	—	0.90–1.20	373		17.70	7.60	43	[18]	
	—[b]	Rep. U.S.[c]	C	—	0.00–0.30	371		22.40	7.80	35	[18]	
	—[b]	Rep. U.S.[c]	C	—	0.30–0.60	362		22.80	7.80	34	[18]	
	—[b]	Rep. U.S.[c]	C	—	0.60–0.90	336		22.70	8.60	38	[18]	
	—[b]	Rep. U.S.[c]	C	—	0.90–1.20	290		22.20	8.90	40	[18]	
	—[b]	Rep. U.S.[c]	D	—	0.00–0.30	230		24.10	9.10	38	[18]	
	—[b]	Rep. U.S.[c]	D	—	0.30–0.60	208		26.10	9.30	36	[18]	
	—[b]	Rep. U.S.[c]	D	—	0.60–0.90	178		25.00	8.20	33	[18]	
	—[b]	Rep. U.S.[c]	D	—	0.90–1.20	146		24.10	8.10	33	[18]	
Water content at 15 bar	Sandy loam	3.9	—	Pressure plate	0.00–0.15	7	g/g	0.03	0.01	18	—[a]	
	Sandy loam	3.9	—	Pressure plate	0.25–0.43	7		0.04	0.02	60	—[a]	
	Sandy loam	3.9	—	Pressure plate	0.48–0.60	7		0.06	0.04	54	—[a]	
	Sandy loam	3.9	—	Pressure plate	0.94–1.07	7		0.08	0.02	26	—[a]	
	—[b]	Rep. U.S.[c]	A	—	0.00–0.30	118	vol-%	4.10	3.40	82	[18]	
	—[b]	Rep. U.S.[c]	A	—	0.30–0.60	119		3.20	2.40	75	[18]	
	—[b]	Rep. U.S.[c]	A	—	0.60–0.90	113		2.90	2.30	81	[18]	
	—[b]	Rep. U.S.[c]	A	—	0.90–1.20	105		2.60	2.30	87	[18]	
	—[b]	Rep. U.S.[c]	B	—	0.00–0.30	880		9.00	4.00	45	[18]	
	—[b]	Rep. U.S.[c]	B	—	0.30–0.60	883		9.40	4.30	46	[18]	
	—[b]	Rep. U.S.[c]	B	—	0.60–0.90	866		9.10	4.40	48	[18]	
	—[b]	Rep. U.S.[c]	B	—	0.90–1.20	866		8.60	4.60	53	[18]	
	—[b]	Rep. U.S.[c]	C	—	0.00–0.30	678		10.80	5.10	48	[18]	
	—[b]	Rep. U.S.[c]	C	—	0.30–0.60	677		12.20	5.60	46	[18]	
	—[b]	Rep. U.S.[c]	C	—	0.60–0.90	652		12.20	6.00	49	[18]	

continued

Table 1 continued

Parameter	Soil texture	Field area (ha)	Hydro group	Measurement method	Sampling depths (m)	N	Units	Mean	SD	C.V.	Reference
	—[b]	Rep. U.S.[c]	C	—	0.90–1.20	582		11.80	5.70	48	[18]
	—[b]	Rep. U.S.[c]	D	—	0.00–0.30	495		14.60	7.60	52	[18]
	—[b]	Rep. U.S.[c]	D	—	0.30–0.60	485		16.90	7.30	43	[18]
	—[b]	Rep. U.S.[c]	D	—	0.60–0.90	437		16.60	7.40	45	[18]
	—[b]	Rep. U.S.[c]	D	—	0.90–1.20	401		15.70	7.60	48	[18]
pH	Sandy loam	3.9	—	Electronic meter	0.00–0.20	20	pH units	5.89	0.23	4	—[a]
	Sandy loam	3.9	—	Electronic meter	0.25–0.46	20		5.51	0.38	7	—[a]
	Sandy loam	3.9	—	Electronic meter	0.48–0.63	20		5.34	0.32	6	—[a]
	Sandy loam	3.9	—	Electronic meter	0.94–1.07	20		5.12	0.31	6	—[a]
	Sandy loam	0.04	—	Electronic meter	0.00–0.15	208		5.80	0.50	9	[5]
	Loam	0.02	—	Electronic meter	0.00–0.15	640		6.40	0.40	7	[5]
	Clay loam	0.04	—	Electronic meter	0.00–0.15	1,040		6.10	0.90	15	[5]
	Clay loam	85	—	Electronic meter	0.40–0.60	100		8.20	0.20	2	[5]
Saturated hydraulic conductivity	Clay loam	150		Steady infiltration 20 plots × 6 depths		120	cm d^{-1}	20.60	24.72[g]	120	[5]
	Sandy loam	15		Soil cores in lab permeameter		64		168.00	319.20[g]	190	[5]
	Sand	0.8		In situ air-entry permeameter		90		316.00	218.04[g]	69	[5]
	Loamy sand	0.4		Soil cores, lab permeameter		12		84.00	57.96[g]	69	[5]
	Silty clay loam	Comp. SCS[h]		Soil cores, lab permeameter		33		3.60	1.73[g]	48	[5]
	Coarse	[h]		Soil cores, lab permeameter		330		18.90	19.47[g]	103	[5]
	Fine	[h]		Soil cores, lab permeameter		287		11.00	12.98[g]	118	[5]
	Silty clay	[h]		Soil cores, lab permeameter		339		6.90	6.35[g]	92	[5]
	Very coarse	[h]		Soil cores, lab permeameter		36		28.10	89.92[g]	320	[5]
	Coarse	[h]		Soil cores, lab permeameter		352		55.60	65.61[g]	118	[5]
	Loamy sand	[h]		Soil cores, lab permeameter		121		71.20	74.76[g]	105	[5]
	Loamy sand	91.6		Soil cores, lab permeameter		5		98.50	79.79[g]	81	[5]
	Sandy loam	91.6		Soil cores in lab permeameter		5		24.10	42.90[g]	178	[5]

Infiltration rate	Silt loam	9.6	0–30 cm infiltration (double ring)	26	cm d^{-1}	203.00	101.50[g]	50	[5]
	Clay loam	150	Steady state	20		14.60	13.72[g]	94	[5]
	Loam	0.9	Steady infiltration (double ring)	1,280		16.80	6.72[g]	40	[5]
	Silty clay loam	0.004	Adjacent infiltrometers along transect	625		6.60	4.69[g]	71	[5]
	Silty clay loam	0.004	Adjacent infiltrometers along transect	125		8.50	4.76[g]	56	[5]
	Silty clay loam	0.004	Adjacent infiltrometers along transect	25		8.50	1.96[g]	23	[5]
	7-series	100	Dougle-ring infiltrometer	20		47.00	37.13[g]	79	[5]
	7-series	100	Inverse auger hole method 150 cm	15		263.00	255.11[g]	97	[5]

[a]Unpublished data from Dougherty Plain field project.
[b]Unavailable.
[c]Represents mean values for the United States.
[d]At zero suction.
[e]By bulk density and particle density.
[f]Unpublished data.
[g]Calculated on basis of mean and C.V.
[h]Comp. SCS, composite SCS data for a given soil series in Imperial Valley, CA.

EXAMPLE APPLICATION

The steps necessary to estimate sample size requirements for evaluation of pesticide leaching are the following (a) Select desired confidence level. (b) Obtain an estimate of variability associated with desired characteristic. (c) Determine acceptable relative tolerable error. (d) Find the intersection point for variability and relative tolerable error from either Figure 1 or 2, depending on selected confidence level. For example, an analysis of pesticide transformation is required. The levels of confidence and tolerable error chosen are 90 and 50%, respectively. An estimate of the variability associated with pesticide transformation is approximately 100% (Table 3). For this example application, a sample size of 13 is estimated, using Figure 1.

Sensitivity analyses can be accommodated by holding relative tolerable error constant and varying the estimate of variability or by varying the desired tolerable error for a given variability. These analyses can be used to accommodate sample size allocations for a given resource budget, to determine the relative increase in precision for larger numbers of samples and to establish minimal requirements for field evaluations.

SELECTION OF SAMPLING SITES

Recall that the classical statistical approach for estimating sample size has randomness as a basic component. In addition, independence among observations is essential to ensure efficiency and unbiased estimates. For field sampling, this implies that randomly selected samples should be obtained only at distances that are spatially independent. These two components, randomness and independence, are necessary to ensure that the estimates of mean and variances calculated are statistically rigorous. An estimate is more likely to be accurate if a large enough sample size is selected. The method presented in this work provides a way to estimate, using random sampling, the total sample size necessary to obtain a population mean of known confidence. It does not provide, however, for actual sample selection, say, within a field. A detailed analysis of sample selection and location is beyond the scope of this article. For purposes of illustration, an ongoing study is briefly described to illustrate one successful approach to the problem.

The selection of sampling sites was a key step in a current study by the EPA and the U.S. Geological Survey to evaluate pesticide migration in a field site located in southwest Georgia. The selec-

Table 2. Mean, standard deviation (SD) and coefficient of variation (C.V.) of inorganic solutes

Parameter	Soil texture	Field area (ha)	Measurement method	Sampling depths (m)	N	Units	Mean	SD[a]	C.V.	Reference
Bromide	Loamy sand	0.64	Solution samplers	0.30–0.00	14	mol/L	0.37×10^{-3}	0.44	118	[5]
	Loamy sand	0.64	Solution samplers	0.60–0.00	14		0.23×10^{-3}	0.21	90	[5]
	Loamy sand	0.64	Solution samplers	0.90–0.00	14		0.27×10^{-3}	0.24	89	[5]
	Sandy loam	0.2	Soil cores	0.60–0.00	18		1.50×10^{-3}	1.50	100	[5]
Chloride	Loamy sand	0.64	Soil cores	0.65–0.00	36	mol/L	0.61×10^{-3}	0.77	127	[5]
	Loamy sand	0.64	Soil cores	1.15–0.00	34		0.91×10^{-3}	0.72	79	[5]
	Loamy sand	0.64	Soil cores	1.85–0.00	29		1.47×10^{-3}	1.12	76	[5]
	Loamy sand	0.03	Soil cores	0.12–0.00	32		0.11×10^{-3}	0.07	67	[5]
	Loamy sand	0.03	Soil cores	0.32–0.00	32		0.04×10^{-3}	0.02	61	[5]
	Sandy-loam loam	16	Soil cores[b]	1.80–6.00	32		4.50×10^{-3}	0.99	22	[5]
	Sandy-loam loam	8	Soil cores[b]	1.80–6.00	16		6.60×10^{-3}	1.98	30	[5]
	Loam sandy-loam	20	Soil cores[b]	1.00–3.60	32		6.40×10^{-3}	6.46	101	[5]
	Loam sandy-loam	13	Soil cores[b]	1.00–4.20	32		7.10×10^{-3}	1.49	21	[5]
	Sandy loam	0.81	Ave. concn.[c]	1.50–6.30	10		15.50×10^{-3}	2.95	19	[5]
	Sandy loam	0.14	Ave. concn.[c]	1.50–6.30	10		13.30×10^{-3}	2.53	19	[5]
	Clay loam	0.14	Ave. concn.[c]	1.50–6.30	10		58.50×10^{-3}	38.61	66	[5]
	Loam	—	Soil cores	0.60–1.20	94		17.50×10^{-3}	10.50	60	[5]
	F. sandy-loam	8	Soil cores	0.90–1.50	142		11.00×10^{-3}	11.22	102	[5]
	F. sandy-loam	2	Soil cores	0.60–1.20	248		15.00×10^{-3}	13.05	87	[5]

[a]Calculated on basis of mean and C.V.
[b]Below root zone.
[c]In vertical profile.

Table 3. Mean, standard deviation (SD) and coefficient of variation (C.V.) of pesticide degradation half-lives and sorption coefficients

Parameter	Soil texture	Field size (ha)	Pesticide	Measurement method	Sampling depth (m)	N	Units	Mean	SD	C.V.	Reference
Degradation	Sandy loam	3.9	Aldicarb (TTR)	LBI	0.00–0.20	10	$t_{1/2}$ (d)	42.00	8.82	21	[9]
	Sandy loam	3.9	Aldicarb (TTR)	LBI	0.25–0.46	10		42.00	15.96	38	[9]
	Sandy loam	3.9	Aldicarb (TTR)	LBI	0.48–0.63	10		47.00	12.22	26	[9]
	Sandy loam	3.9	Aldicarb (TTR)	LBI	9.94–1.07	10		62.00	13.02	21	[9]
	Sandy loam	3.9	Metolachlor	LBI	0.00–0.20	6		18.00	1.98	11	[9]
	Sandy loam	3.9	Metolachlor	LBI	0.25–0.46	3		27.00	8.91	33	[9]
	Sandy loam	3.9.	Metolachlor	LBI	0.48–0.63	3		42.00	2.94	7	[9]
	Sandy loam	3.9	Metolachlor	LBI	9.94–1.07	6		43.00	16.34	38	[9]
	Sandy loam	0.64	Metribuzin	LBI	0.00–0.10	10		36.60	7.72	21	[14]
	Sandy loam	0.64	Simazine	LBI	0.00–0.10	10		27.70	1.91	7	[14]
	—[a]	—	2,4-D	Lab	—	—		16.00	9.01	56	[14]
	—[a]	—	2,4-D	Field	—	—		5.00	5.00	100	[14]
	—[a]	—	2,4,5-T	Lab	—	—		33.00	22.01	67	[14]
	—[a]	—	Atrazine	Lab	—	—		48.00	33.02	69	[14]
	—[a]	—	Atrazine	Field	—	—		20.00	10.00	50	[14]
	—[a]	—	Trifluralin	Lab	—	—		132.00	109.03	83	[14]
	—[a]	—	Trifluralin	Field	—	—		46.00	18.99	41	[14]
	—[a]	—	Bromacil	Lab	—	—		106.00	45.05	43	[14]
	—[a]	—	Bromacil	Field	—	—		349.00	268.03	43	[14]
	—[a]	—	Terbacil	Lab	—	—		50.00	13.00	26	[14]
	—[a]	—	Terbacil	Field	—	—		175.00	155.05	89	[14]
	—[a]	—	Linuron	Lab	—	—		75.00	14.03	19	[14]
	—[a]	—	Linuron	Field	—	—		230.00	67.39	29	[14]
	—[a]	—	Diuron	Field	—	—		328.00	211.89	65	[14]
	—[a]	—	Dicamba	Lab	—	—		14.00	11.99	86	[14]
	—[a]	—	Dicamba	Field	—	—		8.00	1.00	13	[14]
	—[a]	—	Pichloram	Lab	—	—		138.00	93.01	67	[14]
	—[a]	—	Pichloram	Field	—	—		31.00	23.99	77	[14]
	—[a]	—	TCA	Lab	—	—		46.00	55.02	120	[14]
	—[a]	—	Glyphosate	Lab	—	—		38.00	53.01	140	[14]
	—[a]	—	Parathion	Lab	—	—		35.00	29.02	83	[14]
	—[a]	—	Parathion	Field	—	—		18.00	7.99	44	[14]
	—[a]	—	Diazinon	Lab	—	—		48.00	30.00	63	[14]
	—[a]	—	Malathion	Lab	—	—		0.80	0.70	88	[14]
	—[a]	—	Phorate	Field	—	—		7.50	1.80	24	[14]
	—[a]	—	Carbofuron	Lab	—	—		37.00	35.00	95	[14]
	—[a]	—	Carbofuron	Field	—	—		68.00	42.02	62	[14]

continued

Table 3 continued

Parameter	Soil texture	Field size (ha)	Pesticide	Measurement method	Sampling depth (m)	N	Units	Mean	SD	C.V.	Reference
	—[a]	—	Carbaryl	Lab	—	—		22.00	9.00	41	[14]
	—[a]	—	Carbaryl	Field	—	—		12.00	11.00	92	[14]
	—[a]	—	DDT	Lab	—	—		1,657.00	1,628.80	98	[14]
	—[a]	—	Aldrin + dieldrin	Field	—	—		1,237.00	2,454.21	198	[14]
	—[a]	—	Chlordane	Field	—	—		214.00	2,453.49	202	[14]
	—[a]	—	Heptachlor	Field	—	—		426.00	351.88	83	[14]
	—[a]	—	PCP	Lab	—	—		48.00	28.99	60	[14]
Sorption	Sandy loam	3.9	Aldicarb	BE	0.00–0.20	20	K_D L kg^{-1}	0.07	0.03	42	—[b]
	Sandy loam	3.9	Aldicarb	BE	0.25–0.46	20		0.04	0.02	38	—[b]
	Sandy loam	3.9	Aldicarb	BE	0.48–0.63	20		0.04	0.02	56	—[b]
	Sandy loam	3.9	Aldicarb	BE	0.94–1.07	20		0.03	0.01	42	—[b]
	Sandy loam	3.9	Metolachlor	BE	0.00–0.20	20		0.72	0.25	34	—[b]
	Sandy loam	3.9	Metolachlor	BE	0.48–0.63	19		0.25	0.13	50	—[b]

LBI, lab batch incubation; TTR, total toxic residue; BE, batch equilibrium.
[a]Unavailable.
[b]Unpublished data from Dougherty Plain field project.

tion of samples within the site was determined by placing a 15.2 × 15.2 m grid over the field and selecting sampling points (20 for that study) from candidate sites denoted by the intersecting points of the grid. The grid size was selected because the intersecting points provided a reasonably large (greater than 100) population from which to sample and was the most practical for implementation in the field. The grid pattern and randomly selected sampling points are displayed in Figure 6. Similar types of sample selection procedures could be used for evaluating pesticide downward movement.

Part of the ongoing work is directed at evaluating spatial correlations of pesticide application. Confirmation of sample independence was determined by developing semivariograms of the pesticide aldicarb. An example of a semivariogram for aldicarb is displayed in Figure 7. A simple spherical model was used to estimate the range of influence for aldicarb. The apparent range of influence is very small and is estimated to be approximately 1.0 m. On the basis of these data, sampling locations greater than 1.0 m apart were expected to be spatially independent. The range of influence may be affected by any number of factors associated with the application of aldicarb experimental site or intrinsic soil characteristics.

SUMMARY

A method was presented for estimating sample size requirements to produce desired precision for field-scale evaluations of pesticide leaching based on estimates of variability. Estimates of variability were determined from selected spatial variability studies of soil capacity and intensity factors, pesticide transport and transformation characteristics and soil profile concentrations.

The ability to characterize the leaching of pesticides in agricultural fields using such a statistical approach can improve quantitative evaluations of pesticide transport and interpretations of the results of field studies.

REFERENCES

1. **U.S. Environmental Protection Agency, Office of Pesticide Programs.** 1984. Data requirements for pesticide registration: Final rule. *Fed. Reg.* **49**:42856–42892.
2. **Cohen, S.Z., S.M. Creeger, R.F. Carsel** and **C.G. Enfield.** 1984. Potential ground water contamination from agricultural pesticides. In R.F. Krueger and J.N. Seiber, eds., *Treatment and Disposal of Pesticide Wastes.* ACS Sysmposium Series 259. American Chemical Society, Washington, DC, pp. 198–325.

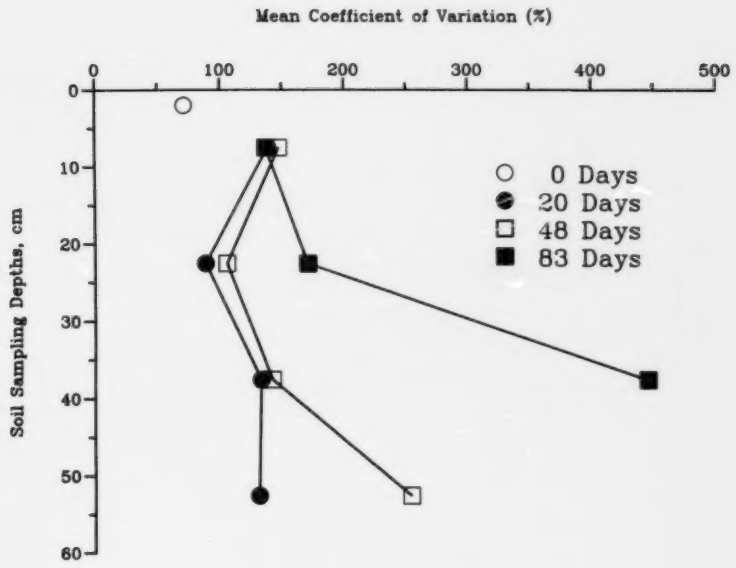

Fig. 3. Aldicarb variability with depth and time after application for Dougherty Plain, Georgia.

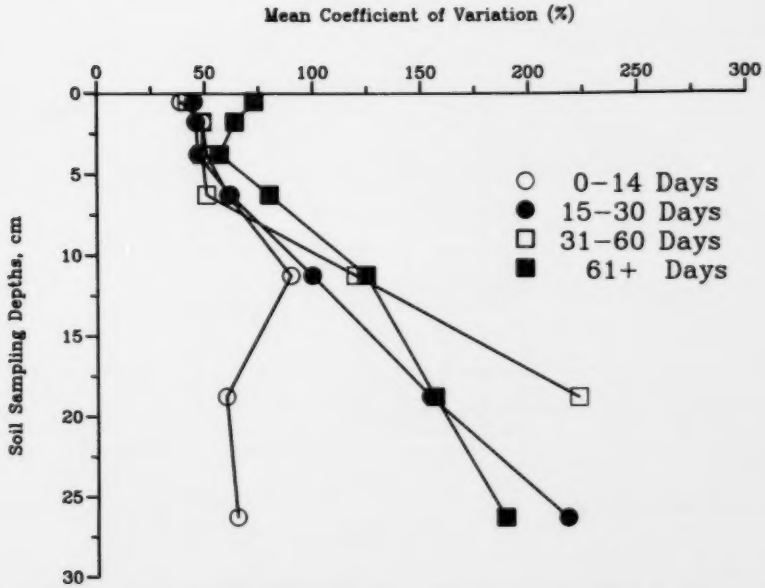

Fig. 4. Atrazine variability with depth and time after application for Watkinsville, Georgia.

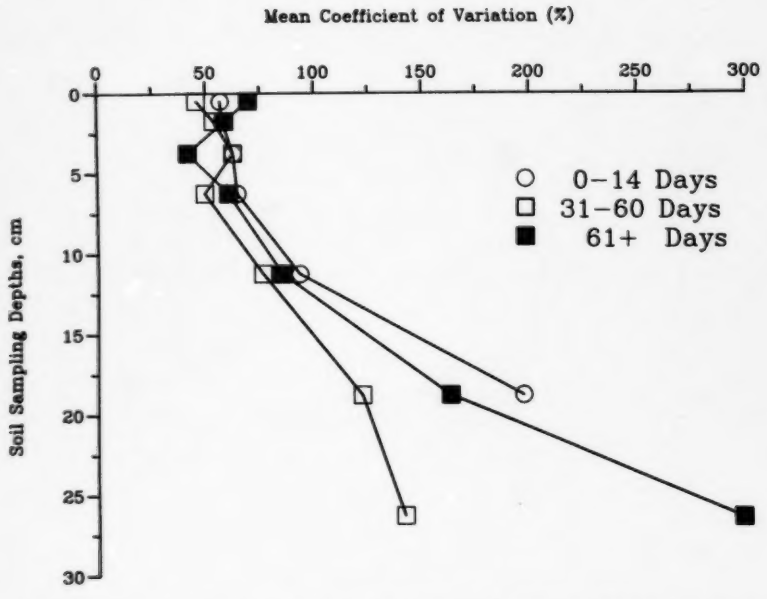

Fig. 5. Propazine variability with depth and time after application for Watkinsville, Georgia.

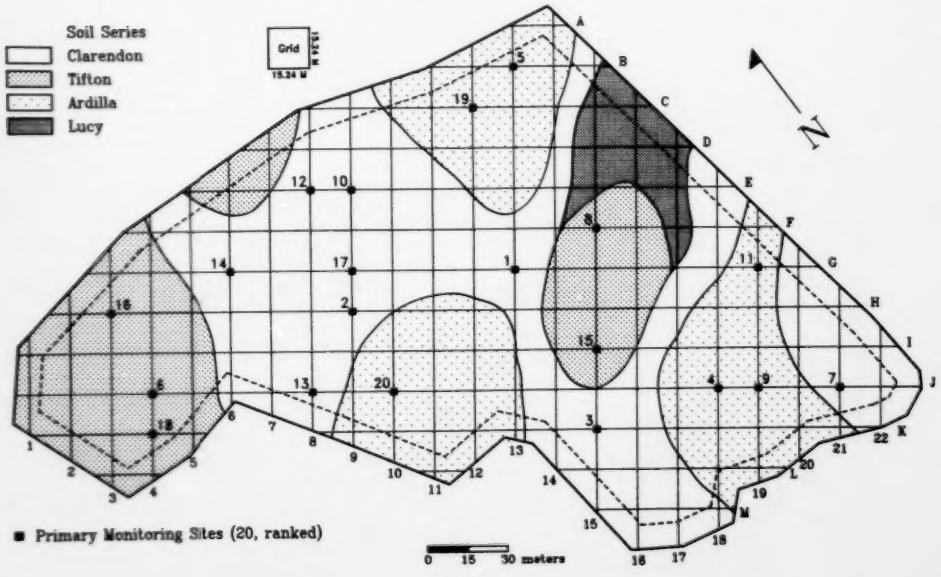

Fig. 6. Illustration of a field design for characterizing pesticide leaching.

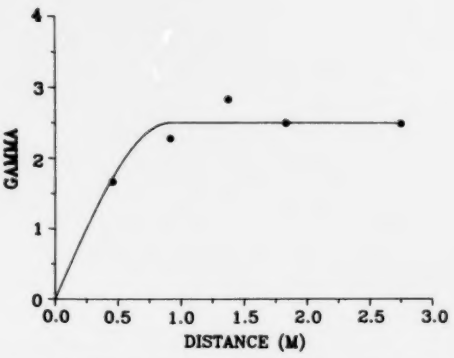

Fig. 7. Developed semivariogram for aldicarb for Dougherty Plain, Georgia.

3. **U.S. Environmental Protection Agency.** 1977. Waste disposal and its effects on groundwater. Report to Congress. Washington, DC, pp. 81–107.
4. **Carsel, R.F.** and **C.N. Smith.** 1984. Rachael Carson's *Silent Spring* and the impact of pesticides—past and present—on groundwater contamination. Paper presented at the American Chemical Society Symposium on *Silent Spring* Revisited, Philadelphia, PA, August 28, 1984. (in press).
5. **Jury, W.A.** 1985. Spatial variability of soil physical parameters in solute movement: A critical literature review. EPRI EA-4228. Electric Power Research Institute, Palo, Alto, CA, pp. 2.1–2.11.
6. **Nielson, D.R., J.W. Biggar** and **K.T. Ehr.** 1973. Spatial variability of field measured soil-water properties. *Hilgardia* **42**:215–259.
7. **Sharma, M.L.** and **A.S. Rogowski.** 1985. Hydrological characterization of watersheds. In D.G. DeCoursey, ed., *Proceedings*, Natural Resources Modeling Symposium, Pingree Park, CO, October 16–21, 1983, pp. 291–295.
8. **Warrick, A.W.** and **D.R. Nielson.** 1980. Spatial variability of soil physical properties in the field. In D. Hillel, ed., *Applications of Soil Physics.* Academic Press, New York, NY, pp. 319–344.
9. **Rao, P.S.C., K.S.V. Edvardsson, L.T. Ou, R.E. Jessup, P. Nkedi-Kizza** and **A.G. Hornsby.** 1986. Spatial variability of pesticide sorption and degradation parameters. In W.Y. Garner, R. Honeycutt and H.N. Nigg, eds., *Evaluation of Pesticides in Groundwater.* ACS Symposium Series 315. American Chemical Society. Washington, DC, pp. 100–115.
10. **Walker, A.** and **P.A. Brown.** 1983. Spatial variability in herbicide degradation rates and residues in soil. *Crop Protection* **2**:17–25.
11. **Amoozegar-Fard, A., D.R. Nielson** and **A.W. Warrick.** 1982. Soil solute concentration distributions for spatially varying pore water velocities and apparent diffusion coefficients. *Soil Sci. Soc. Am. J.* **46**:3–8.
12. **Rao, P.S.C.** and **R.J. Wagenet.** 1985. Spatial variability of pesticides in field soils: methods for data analysis and consequences. *Weed Sci.* **33**:18–24.
13. **Rao, P.S.C., P. Knedi-Kizza, J.M. Davidson** and **L.T. Ou.** 1983. Retention and transformation of pesticides in relation to nonpoint source pollution from croplands. In F. Schaller and G. Bailey, eds., *Agricultural Management and Water Quality.* Iowa State University Press, Ames, IA, pp. 126–140.
14. **Ou, L.T., J.M. Davidson, P.S.C. Rao** and **W.B. Wheeler.** 1982. Pesticide transformations in soil. In P.S.C. Rao and J.M. Davidson, eds., *Retention and Transformation of Selected Pesticides and Phosphorus in Soil-Water Systems: A Critical Review.* EPA-600/S3-82-060. U.S. Environmental Protection Agency, Athens, GA, pp. 40–73.
15. **Bresler, E.** and **G. Dagan.** 1981. Convective and pore scale dispersive solute transport in unsaturated heterogeneous fields. *Water Resources Res.* **17**:1683–1693.
16. **Jury, W.A.** 1982. Simulation of solute transport using a transfer function model. *Water Resources Res.* **18**:363–368.
17. **Smith, C.N., D.S. Brown, J.D. Dean, R.S. Parrish, R.F. Carsel** and **A.S. Donigian, Jr.** 1985. Field agricultural runoff monitoring (FARM) manual. EPA/600/3-85-043. U.S. Environmental Protection Agency, Athens, GA.
18. **Carsel, R.F., R.S. Parrish, R.L. Jones, J.L. Hansen** and **R.L. Lamb.** 1986. Characterizing the uncertainty of pesticide leaching in agricultural soils. *J. Contaminant Hydrology* (in press).
19. **Smith, C.N., R.A. Leonard, G.W. Langdale** and **G.W. Bailey.** 1978. Transport of agricultural chemicals from small upland piedmont watersheds. EPA-600/3-78-056. U.S. Environmental Protection Agency, Athens, GA.

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.